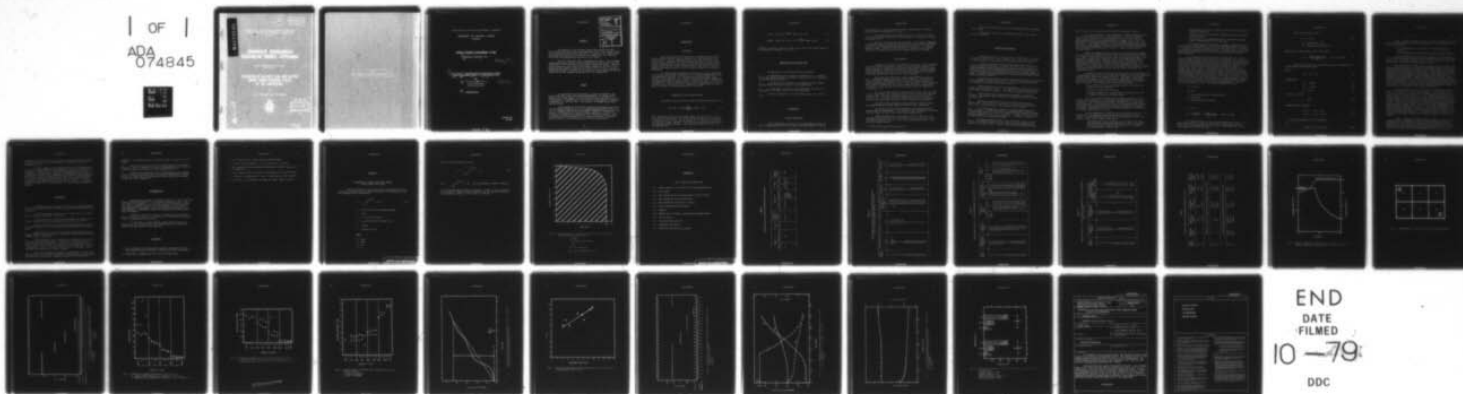AD-A074 845   DEFENCE RESEARCH ESTABLISHMENT OTTAWA (ONTARIO)   F/G 10/3
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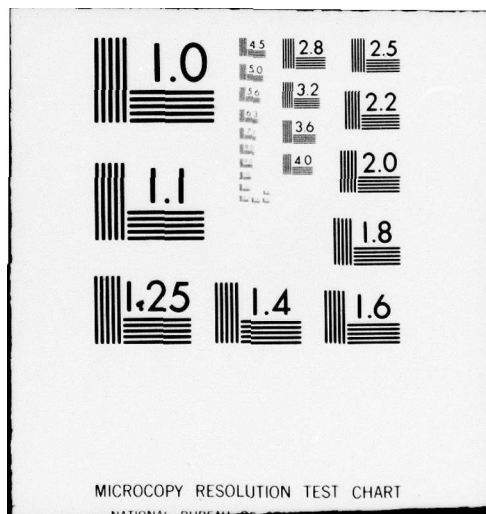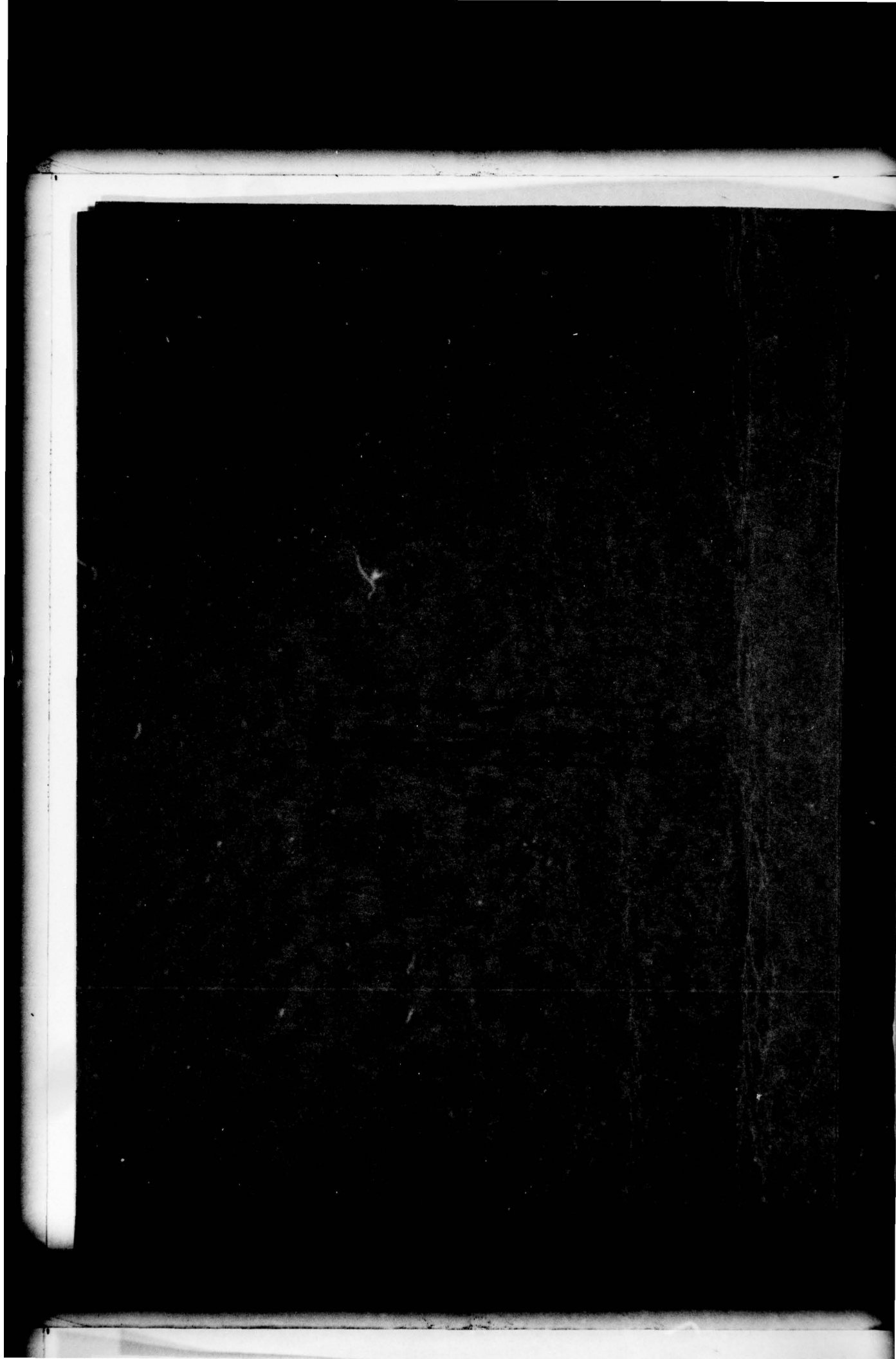UNCLASSIFIED   DREO-TN-79-15   NL

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EVALUATION OF BB-248/U LEAD ACID BATTERY DURING CHARGE-DISCHARGE CYCLES AT LOW TEMPERATURE

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ABSTRACT

The behaviour of the lead-acid battery type BB-248/U has been studied during many consecutive charge-discharge cycles. The cranking current and the minimum terminal voltage were 285 A (or 300 A) and 6 V, respectively. The working temperature was successively room temperature, 0°C, -20°C and -40°C while the rechargeability period was only 2 hours.

This work shows that such a rechargeability period - with a maximum charge current and an applied terminal voltage of 20 A and 14.25 V (or 16 V), respectively - is far too short to completely recharge the battery. Moreover, the rechargeability rate is only very slightly affected by the value of the maximum applied terminal voltage in the range of 14.25 V to 16 V. Finally, a significant decrease of reserve capacity measured at room temperature has been observed after many charge-discharge cycles at low temperatures.

RÉSUMÉ

Le comportement de l'accumulateur au plomb type BB-248/U a été étudié durant des cycles consécutifs charge-décharge. Le courant de décharge et le voltage minimal de sortie étaient de 285 A (ou 300 A) et 6 V, respectivement. La température de travail était successivement la température ambiante, 0°C, -20°C et -40°C. Par ailleurs, la recharge durait deux heures seulement.

L'étude révèle qu'une durée de recharge de deux heures avec un courant de recharge maximum de 20 A et un voltage maximum imposé de 14.25 V ou 16 V est largement insuffisant pour pleinement recharger l'accumulateur. Par ailleurs, l'élévation de la limite du voltage imposé de 14.25 V à 16 V se traduit par une augmentation négligeable de la vitesse de recharge. Enfin, on a observé une forte diminution de la capacité de réserve à l'ambiante après une série de cycles charge-décharge aux basse températures.

INTRODUCTION

BACKGROUND

Lead acid batteries are largely used by Canadian Forces to start vehicle engines. However, weather conditions are very severe especially during Arctic winter when temperatures may be less than -40°C for a long period of time. Behaviour of a lead acid battery is then affected significantly; rechargeability of the battery is very poor while capacity and discharge terminal battery voltage decrease markedly from -20°C to -40°C (1). Moreover, the energy required to start an engine increases with decreasing temperature.

For these reasons, cranking characteristics of several commercial and military batteries were determined (1,2) at several temperatures between room temperature and -40°C. All these batteries were previously fully charged at room temperature (1). However, batteries are usually charged at low temperatures during a limited period of time in the field. Valeriote and associates (1) recently suggested testing cranking characteristics of cold soaked military batteries previously charged at low temperatures for only two hours to simulate the charging conditions in the field.
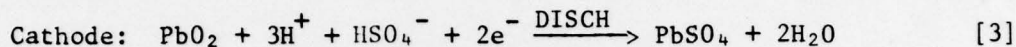
CHEMISTRY OF THE LEAD-ACID SYSTEM

The overall reaction occurring inside the lead-acid battery is (3):

$$Pb + PbO_2 + 2H_2SO_4 \xrightarrow[DISCH]{CH} 2PbSO_4 + 2H_2O \qquad [1]$$
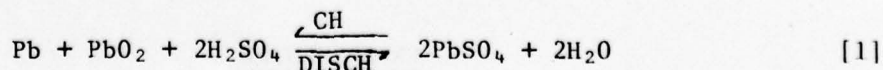
Acid, lead dioxide and lead are consumed during a discharge while lead sulfate and water are produced. ΔH of the overall reaction at room temperature calculated from $\Delta H°$ of each chemical species (4) is -359,446 J (or -85,992 cal) per mole of H_2SO_4 consumed. The minus sign (-) means that the reaction is exothermic during a discharge. The overall reaction is the sum of the two reactions (5):

Anode: $Pb + HSO_4^- \xrightarrow{\text{DISCH}} PbSO_4 + H^+ + 2e^-$ [2]

Cathode: $PbO_2 + 3H^+ + HSO_4^- + 2e^- \xrightarrow{\text{DISCH}} PbSO_4 + 2H_2O$ [3]
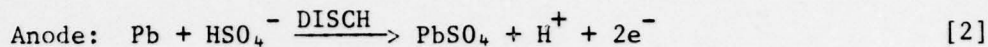
Therefore, reaction of 2 moles of H_2SO_4 with 1 mole of PbO_2 should result in the production of 193,000 C or 53.61 Ah.

OBJECTIVES OF THE PRESENT WORK

The objectives of the present work are the following:

1.   To determine how short term (2 h) charging at low temperatures affects the charge acceptance and cranking capacity at the same temperature of the 248/U military battery.

2.   To investigate the influence of the magnitude of the limiting charging voltage on charge acceptance at low temperatures.

3.   To investigate the effects of charge-discharge cycling at low temperature on the reserve capacity at room temperature.

Tests were carried out at room temperature (RT), 0°C, -20°C and -40°C.

EXPERIMENTAL

BATTERY PREPARATION

A dry charged battery was filled with approximately 1100 ml per cell of reagent grade sulfuric acid having a specific gravity of 1.28 at

room temperature. The size, weight and other characteristics of BB-248/U military battery are summarized in Table I.

The wet battery was fully charged at R.T. at a rate of 5A (C/20). Note that the battery was generally fully recharged at a current of 5A before a discharge at R.T.

Below R.T. batteries were charged inside a cold chamber, THERMOTRON S-4 MINI MAX. However, an explosion may occur due to ignition of appreciable amounts of oxygen and hydrogen evolving during a charge (1). To avoid any explosion hazard, a manifold system was used to vent gases to the exterior as well as to introduce a small flow of nitrogen into the cold chamber.

TEST PROCEDURE

Initially, two values of the reserve capacity (R.C.) were determined in order to reduce the influence of memory effect on further results. The reserve capacity is defined by North American manufacturers as the discharge time in minutes to a 1.75 V/cell cut-off at a rate of 25A. However, reserve capacity is quoted in this report in Ah rather than minutes for a discharge at the same current and to the same cell cut-off voltage.

The battery was subjected to further charge-discharge cycles at R.T. to determine cranking characteristics near 300A (3C). The system was fully recharged at room temperature at a current of 5A (C/20) between two consecutive discharging periods. Several cycles were done at room temperature while terminal voltage and current were recorded with time. During these experiments, a lower voltage limit of 6V was used to mark the completion of a discharge (1,2).

R.T. cycles were followed by several cycles at 0°C, -20°C and -40°C. At these temperatures, the charging period was only two hours with a maximum current of 20A (C/20) and a specified voltage limit (L.V.C.)* of either 14.25V or 16V. The curves in Figure 1 illustrate the typical variation of current and applied voltage with time during a charge at low temperature.

Internal battery resistance was measured with a Hewlett-Packard milliohmmeter Model No. 4328A (1000 Hz) before and after a discharge.

The battery was charged and discharged after temperature equilibration with the surrounding. It was charged in the cold chamber and removed from the chamber for only a few minutes before cranking tests.

During the second set of experiments (L.V.C. of 16V), the acid temperature was recorded in the cell #2 (Figure 2) with a thermistor probe. The specific gravity of acid in cells #3 and #5 was measured before, during and after charging periods.

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* Or maximum applied voltage (Figure 1).

Finally, reserve capacity at R.T. was determined after low temperature cycling.

Experimental conditions are summarized in Table II and Figure 3 (L.V.C. of 14.25 V).

RESULTS AND DISCUSSION

Experimental results for the first set of tests (L.V.C. of 14.25 V) are given in Tables III to V and in Figures 4 to 6. They are used further to compare results of the second set of experiments (L.V.C. of 16 V).

Duration of charging and discharging periods under different experimental conditions are given in Tables II and III (L.V.C. of 14.25 V). Charge consumption during charging periods, electrical work (W) done by the system and capacity (C) are summarized in Table III. It should be noted that the electrical work (W) was determined from terminal voltage versus time curves. An example of the determination of electrical work (W) done by the system is given in Appendix 1.

In addition, the internal battery resistance is given in $m\Omega$ before and after discharges in Table IV while values of R.C. at room temperature after low temperature cycling are summarized in Table V.

Charge consumed and capacity corresponding to a LVC of 14.25 V are graphically represented in Figure 4. The electrical work consumed and done by the system are given in Figure 5. The results of Figure 4 reveals that:

(1)   Capacity and charge consumed decrease markedly as temperature decreases. For example, three C capacity is roughly 45 Ah at R.T. but only two Ah at -40°C.

(2)   Capacity is significantly lower than charge consumed during a charge at R.T. These values are respectively 36 and 58.5 Ah during second cycle at R.T. but they are very close together at 0°C and below.

(3)   At a fixed temperature, capacity is markedly higher during the first discharge. It should be noted that the battery was previously charged at higher temperatures. At -20°C, the capacity is nearly 22 Ah for the first discharge compared to 15 Ah for the second one. In addition, capacity decreases slightly for the subsequent cycles.

A comparison between Figures 4 and 5 shows that electrical work done (W) and consumed during each cycle change in much the same manner as capacity and charged accepted. However, electrical work accepted is always

markedly higher than the electrical work done by the battery (Figure 5).

The reserve capacity at room temperature is markedly affected by previous charge-discharge cycling at low temperature. In fact, the reserve capacity was initially 85 ± 3 Ah compared to only 63.5 ± 1.5 Ah (Table V) after completion of the test program outlined in Figure 3 (LVC of 14.25 V). Similarily, a battery after being subjected to a program having a LVC of 16 V had only 14 ± 4 Ah reserve capacity. It should be noted that reserve capacity comes back to approximately its initial value of 82 ± 7 Ah after being stored fully charged for two months at +4°C (Table V). This is called here the "recovery effect".

Dodson (8) observed that the capacity of a positive plate increases as the mass ratio $\alpha PbO_2/\beta PbO_2$ decreases. This is due to the fact that βPbO_2 has a higher average oxidation value and can be more easily discharged. These considerations suggest that formation of αPbO_2 is preferentially promoted during R.T. charging after a low temperature cycling. Consequently, RC is lower during initial cycles. However, the battery recovers after a long storage because a large part of αPbO_2 should be transformed in βPbO_2. In addition, ice formation inside pores at low temperature (6) may promote shedding of the plates and contribute to a lower reserve capacity value after low temperature cycling.

Examination of the positive and negative plates, of the separators and the electrolyte should allow us to clarify the reason(s) for loss of capacity and recovery effects after a low temperature cycle. The battery is internally affected by the passage of a current through it, especially a high current. Thus, total internal resistance of the battery changes during a discharge as shown in Figure 6. This figure shows that internal resistance:

- has a higher value after a discharge except at -40°C where the change of I.R. is negligible;

- increases as temperature decreases;

- increases slightly with cycling except at -40°C where the rate of change in resistance increases sharply.

The I.R. of a lead accumulator may depend on the amount of lead sulfate on the electrodes, on concentration and temperature of the acid, on resistance of the separators and, possibly, formation of ice inside electrode pores (6,7). Thus, formation of $PbSO_4$ on the plates and acid depletion in the pores during a discharge should increase the internal resistance of the system. The increase in I.R. with increasing temperature is attributed to a higher conductivity of the acid.

The acid temperature and density may also vary during cycling. The variation of acid temperature near the gas-liquid interface is shown in Figure 7. The surrounding temperature and the cranking current were -20°C and 285 A respectively. Figure 7 shows that:

- acid temperature before discharge is a few degrees (°C) higher than the initial surrounding temperature. This is attributed to the fact that the battery was removed from the cold chamber a few minutes before a cranking test;

- approximately one minute is required before there is a noticeable change in temperature;

- temperature of the acid increases continuously during a constant current discharge;

- the increase in acid temperature during a discharge is several degrees: approximately 8.2°C in this case.

The following figure (#8) shows the increase in temperature due to discharge (ΔT) plotted against the duration of cranking periods. Note that ΔT is graphically defined in Figure 7. The general trend is that ΔT increases as the discharge period increases (Figure 8). From this graph, a ΔT of 9.5°C approximately corresponds to a period of 8 minutes while 5.5°C represents only two minutes.

Let us analyze now the main causes of battery warm up. It was previously seen that the overall reaction occurring inside a lead-acid accumulator is highly exothermic during lead sulfate formation. If we assume that all the electrons produced by this reaction go through the external electrical circuit then consumption of one mole reactant theoretically results in the production of 53.61 Ah while the heat evolved is equal to 85,992 cal (5.7145×10^{-3} kWh). Heat is also generated by the Joules effect. This thermal energy should serve to warm up the system. To show the relationship between the heat evolved due to exothermic reaction (E_T), the Joules effect (E_J) and the heat absorbed to warm up the battery (E_W), the terms E_T, E_J and E_W are evaluated in the following example. In the case of cycle No. 13 (0°C, LVC of 16 V) (Figure 9) the measured capacity to a minimum battery voltage of 6V was 27.6 Ah. The average total internal resistance, discharging current and ΔT were respectively 5.4 mΩ, 285 A and 3.8°C approximately. From the previous section, E_T of 2.942×10^{-3} kWh corresponds to 27.6 Ah.

E_J is equal to:

$$E_J = RI^2t \qquad [4]$$

R: total internal battery resistance (mΩ)

I: current (A)

t: discharging period (seconds)

t = 344 sec

$$E_J = \frac{5.4 \times 10^{-3}}{4.184} \times \frac{(285)^2 \times 344}{15.048 \times 10^6} = 2.396 \times 10^3 \text{ kWh} \qquad [5]$$

The specific heat of the acid, the equivalent mass of water of the whole battery and ΔT are needed to evaluate E_W. The amount of acid was 8504 g while the experimental value for a mass of water equivalent of the dried charged accumulator was 1368 g.

Using the following equation:

$$E_W = m \, Cp \Delta T \qquad [6]$$

Cp: specific heat cal/g

ΔT: temperature increasing (°C)

Substitution of these terms by their values gives:

$$E_W = \frac{(8504 + 1368) \times 3.8}{15.048 \times 10^6} = 2.493 \times 10^{-3} \text{ kWh} \qquad [7]$$

Calculation of E_W by this method supposes that the measured ΔT is representative of the whole battery.

Hence:

$$E_T \overset{\sim}{\sim} E_J \overset{\sim}{\sim} E_W \qquad [8]$$

Remember that

$$E_T \propto \text{charge} \qquad [9]$$

$$E_T \propto \text{capacity} \qquad [10]$$

$$E_T = K_1 I t \qquad [11]$$

while K_1: constant

$$E_J = RI^2 t \qquad [12]$$

Summation of $E_T + E_J$ gives:

$$E_T + E_J = K_1 I t + RI^2 t \qquad [13]$$

$$E_T + E_J = (K_1 I + RI^2) t \qquad [14]$$

To a first approximation, $\Delta T \propto$ heat generated.

So,

$$\Delta T \propto (E_T + E_J) = (K_1 I + RI^2) t \qquad [15]$$

$$\Delta T \approx (K_1 I + R I^2) t \qquad\qquad\qquad [16]$$

Under a constant discharging current ΔT must vary linearly with time when the internal resistances change only slightly. This correlation is confirmed experimentally:

- ΔT is proportional to the duration of the discharge period (Figure 8).

- ΔT is proportional to time during any given discharge (Figure 7).

However, measured ΔT values are not expected to be representative of the warm up of the whole system when the discharge time is too short (less than 1.5 min). Therefore, evaluation of E_W is very speculative at very low temperatures (-40°C) where discharge times are short.

More information is needed during charging periods to evaluate the heat generated in the system. Compared to discharging periods, the amount of gassing is relatively high during charging periods and, consequently, oxygen and hydrogen evolution reaction should consume a large part of the charging current and energy accepted by the accumulator. Heat consumed by the gassing reactions may be large compared to heat consumed by the transformation of lead sulfate to lead dioxide. However, determination of the heat consumed by gassing is impossible without knowledge of the amount and composition of gas evolved during charging. In any case, the heat consumed by gassing reactions and by the transformation of lead sulfate into lead dioxide should contribute to a slow down of the rate at which the battery warms up. Moreover, battery warm up is observed to be markedly higher during overcharging.

Charging currents were very low compared to discharging current: less than 20A (Figure 10) and 285 A, respectively. Thus, the rate of increase in temperature is higher during a discharge as illustrated in Figures 7 and 10, where the ratios $\Delta T(°C)/t$ (h) are approximately 96 during a discharge compared to only 0.62 during a charge. During charging periods it is observed that ΔT is proportional to the charging current as shown in Figure 10. For example, ΔT is 1.2°C and 4°C (approximately) for an average charging current of 7 and 14.35 A respectively. It should be noted that the average charging current increases with a higher value of initial temperature. A value of average charging current of 1.23, 7 and 14.35 A corresponds to an initial temperature of -40°C, -20°C and 0°C respectively (Figures 10 and 11). Battery warm up is negligible at -40°C because the charging current is very low at this temperature (Figure 11). The higher the initial charging current, the greater is the warm up effect and the average charging current will be larger.

A way to increase the initial charging current is to use a higher charging voltage. Experimental values of charge accepted and capacity corresponding to two different charging voltages are compared in Figure 12. However, only a very slight shift of charge accepted and capacity was observed when the charging voltage was increased from 14.25 to 16 V. The increase in the charge accepted and the capacity is only 0.5 Ah at -40°C.

Extrapolation of these results suggests that a very large charging voltage should be used ($\simeq$ 30 V) to increase markedly the charging rate at low temperature (-40°C).

It can be argued that the charging period at low temperature was very short: 2 hours compared to approximately 14 hours at R.T. (Table II), except at 16 V where the battery was also charged during 2 hours at R.T. Consequently, the battery was progressively discharged during cycling at low temperature. This was further confirmed by acid specific gravity measurements after two hours of charging under an LVC of 16 V. Thus the capacity of a partially discharged battery is lower than the capacity of a fully charged one: 21 Ah (Table III) against 10.8 Ah (1) at -40°C. A charging period of 14 hours at -40°C should result in a larger charge acceptance and capacity.

CONCLUSIONS

1.   A charging period of two hours (LVC of 14.25 V, maximum current of 20A) is far too short to fully recharge a previously deeply discharged lead accumulator.

2.   A larger LVC during charging has only a small effect on rechargeability rate and, consequently, on capacity.

3.   Charge accepted and capacity decrease markedly as temperature decreases, especially when the surrounding temperature is below -20°C.

4.   Capacity and electrical work done are closely related with charge and energy accepted by the lead accumulator during charging at low temperature.

5.   Battery warm up is lower during charging than discharging mainly because currents are very different. However, the battery warm up increases markedly during an overcharge.

6.   Initial charging current increases with increasing initial temperature and acid warm up is promoted. Furthermore, the charging current is higher at higher acid temperatures. However, the charging current (LVC of 14.25 V) is very low at -40°C: approximately 1A and, consequently, warm-up is negligible. A way to promote the acid warm up is by applying a strong discharge (short-circuit) just before a charge.

7. ΔT of the acid during a discharge is proportional to time and discharging period. We proposed an explanation which considers two heat sources: the Joule effect (E_J) and the exothermic reaction (E_T) of lead sulfate

formation. It should be noted that calculated values of E_T and E_J are very similar.

8.   Due to the very low value of the charging current at low temperatures (T < -20°C), a relatively low value of the maximum current - near 5 A - can be set without any slow down of the rechargeability rate.

9.   Considering the relatively long period during which the charging current is equal to the maximum value set at higher temperatures (T ≥ 0°C), the use of a higher value of maximum current should increase the rechargeability rate of the accumulator.

RECOMMENDATIONS

1.   Determine the influence of temperature from RT to -60°C on the total internal battery resistance of a fully charged accumulator at rest. These tests should be performed at four different values of acid specific gravity from 1.10 to 1.28 g/cm^3 (at RT). Thus, the magnitude of the influence of acid temperature and concentration on internal battery resistance will be known separately. Furthermore, examine the compatibility of these results with ice formation.

2.   Clarify the reasons for the loss of capacity and recovery effect after low temperature cycling by the examination of the positive and negative plates, the separators and electrolyte.

3.   In the future, a 14-hour charging period should be used at low temperature. This is approximately the time required to fully recharge a deeply discharged battery at room temperature.

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APPENDIX 1

CALCULATION OF ELECTRIC WORK FROM TERMINAL
VOLTAGE VERSUS TIME CURVES

Electric work done by the battery during a discharge between t=0 (when load is applied) and t=t_{6V} which correspond to time required to reach 6V is mathematically represented by:

$$W = \int_{t=0}^{t=t_{6V}} V.I.\, dt \qquad [A1]$$

W = electrical work done during discharge

t = time

t = 0 when load is applied

t = t_{6V} time required to reach 6 volts

I = current

V = terminal voltage

UNITS

W : watts

V : volts

t : sec

I : A

Under a constant discharging current,

$$W = I \int_{t = 0}^{t = t_{6V}} V \, dt \qquad\qquad [A2]$$

Term $\int_{t = 0}^{t = t_{6V}} V \, dt$ can be determined by graphic integration
of V versus time curves (Figure A-1) between $t = 0$ and $t = t_{6V}$. The product
of this value by current (I) gives electrical work (W) done by the system.
In the example of Figure A-1, W is equal to 0.208 kWh.
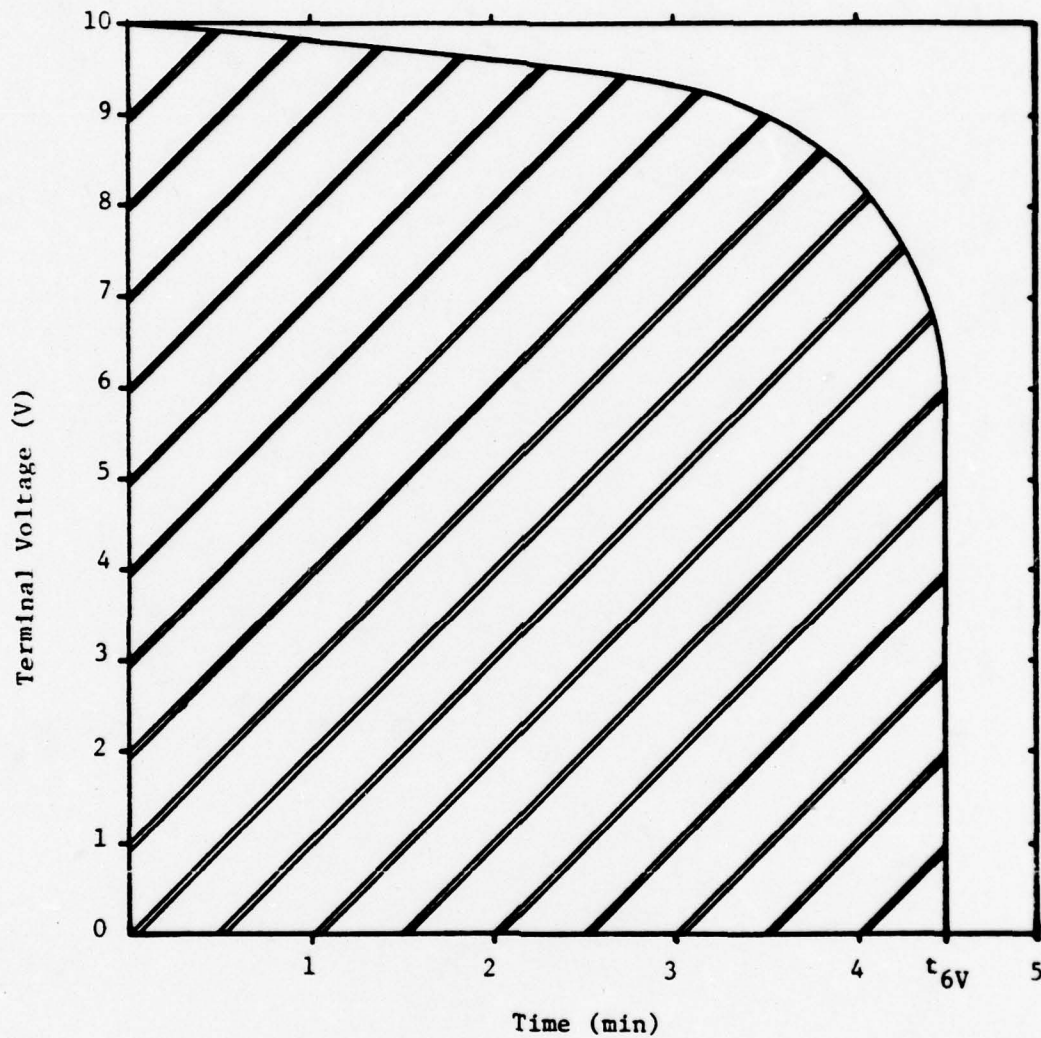
Fig. A1: Typical variation of terminal voltage (V) with time during a
          285 A discharge (Cycle No. 12).

$$S = \int_{t=0}^{t=t_{6V}} \Delta V dt = 82.2 \ (V\text{-}min)$$

$$W = I \cdot S = 0.208 \ kWh$$

t_{6V}:   time corresponding to 6 V.

APPENDIX II

LIST OF PARTICULAR SYMBOLS USED

C : nominal capacity of the battery (20 h discharging period)

CN : cycle number

E_T : heat evolved due to the transformation of PbO_2 in $PbSO_4$

E_J : heat evolved due to the Joules effect

E_W : *heat absorbed by the battery to warm up*

IR : total internal battery resistance

K_1 : constant

LVC: maximum value of applied voltage during charging periods

RC : reserve capacity

RT : room temperature near 20°C

ΔT : temperature increasing

W : electrical work done by the battery

TABLE I

Characteristics of Type BB 248/U Military Battery

Number of		Vented or Sealed	Area of a Single Side of a Plate	Separator		Weight		Nominal Capacity Ah
Cells	Plates/Cell			Thickness	Material	Dry	Wet	
6	23	V	144 cm^2	0.142 cm	resin impregnated paper	23.92 kg	32.43 kg	100

TABLE II

Experimental Conditions During Charge-Discharge Cycles
With a Maximum Charging Voltage of 14.25 V

Cycle Number	Charging Current (A)	Duration of Charging (h)	End of Charging Voltage or Voltage Limit (V)	Temp. of Charging (°C)	Discharge Current (A)	Temperature of Discharge (°C)
1	5	16.2	15.35	R.T.	25	R.T.
2	25/5/2.5	14.4	16.12	R.T.	25	R.T.
3	5/0.5	21.6	16.13/15.3	R.T.	300	R.T.
4	5	13.44	16.25	R.T.	200	R.T.
5	5	12.73	16.56	R.T.	300	R.T.
6	5	27.2	16.29	R.T.	300	R.T.
7	5	14.2	16.73	R.T.	300	R.T.
8	5	11.72	16.65	R.T.	300	0
9	20	2	14.25	0	285	0
10	20	2	14.25	0	286	0
11	20	2	14.25	0	285	0
12	20	2	14.25	0	285	-20
13	20	2	14.25	-20	285	-20
14	20	2	14.25	-20	285	-20
15	20	2	14.25	-20	285	-20
16	20	2	14.25	-20	285	-40
17	20	2	14.25	-40	285	-41
18	20	2	14.25	-41.5	285	-41.5
19	20	2	14.25	-41	285	-41
20	20	2	14.25	-41	285	-41.5

TABLE III

Experimental Results of Charge-Discharge Cycles (LVC of 14.25 V)

Cycle Number	Temperature of Charging (°C)	Charge Consumption (Ah)	Discharging Time (Min.)			Electrical Work Done (kWh) (Limit – 6V)		Capacity (Ah)		
			10.5V	9V	6V	9V	6V	10.5V	9V	6V
1	R.T.	81.53	212.3			1.054(10.5 V)		87.47		
2	R.T.	107.4	200.2			0.999(10.5 V)		82.36		
3	R.T.	136.8		7.93	9.18	0.408	0.470		39.62	42.4
4	R.T.	59.94		9.04	9.43	0.461	0.481		45.2	47.18
5	R.T.	60.00		7.67	8.31	0.394	0.43		38.25	42.1
6	R.T.	103.1		8.41	9.03	0.434	0.467		42.07	45.45
7	R.T.	76.42		8.09	8.73	0.416	0.447		40.5	44
8	R.T.	58.6		6.25	7.23	0.311	0.357		31.25	36.17
9	0	28.77		5.89	6.44	0.289	0.317		28.08	31.0
10	0	27.99		5.08	5.71	0.246	0.279		24.21	27.6
11	0	25.99		4.83	5.47	0.235	0.267		22.96	26.3
12	0	25.93		3.43	4.53	0.157	0.208		16.27	21.8
13	-20	15.44		2.32	3.07	0.108	0.140		11.0	14.57
14	-20	13.51		2.01	2.73	0.093	0.124		9.54	12.98
15	-20	12.29		1.83	2.48	0.085	0.113		8.71	11.8
16	-20	11.37		→0	0.92	→0	0.0357		→0	4.5
17	-40	2.2		→0	0.73	→0	0.0273		→0	3.48
18	-41.5	2.28		→0	0.22	→0	0.007		→0	1.0
19	-41	1.64		→0	0.42	→0	0.0151		→0	2.1
20	-41	2.02		→0	0.46	→0	0.0159		→0	2.2

TABLE IV

Internal Battery Resistance Before and Immediately After Discharges
(LVC = 14.25 V)

Cycle Number	Temperature of Charging (°C)	Temperature of Discharging (°C)	Internal Battery Resistance (mΩ)	
			Before Discharge	After Discharge
1	R.T.	R.T.	–	–
2	R.T.	R.T.	–	–
3	R.T.	R.T.	4.6	–
4	R.T.	R.T.	–	–
5	R.T.	R.T.	4.6	5.35
6	R.T.	R.T.	4.2	5.4
7	R.T.	R.T.	4.4	5.2
8	0	0	4.75	5.40
9	0	0	4.6	5.65
10	0	0	4.75	5.5
11	0	0	3.7	5.4
12	0	-20	5.6(-20)	6.1
13	-20	-20	5.6	6.3
14	-20	-20	5.6	6.4
15	-20	-20	5.6	6.4
16	-20	-40	8.7	8.7
17	-40	-41	9.6	9.1
18	-41.5	-41	9.4	–
19	-41	-41	10.7	10.8
20	-41	-41	10.5	10.9

TABLE V

Maximum Applied Voltage During Charging (14.25 V)

Cycle Number	Charging Current (A)	Duration of Charging (h)	Discharging Time 10.5 V Limit	Electrical Work Done (kWh)	Reserve Capacity (Ah)
21	5	20.3	149	0.743	62.08
22	5	13.87	115.25	0.779	64.69
Storage of a Fully Charged Battery During 2 Months at +4°C					
23	5	4	201.18	0.987	83.83
24	5	18.5	191.77	0.950	79.9
25	5	20	180.95	0.892	75.39
Previous Maximum Applied Voltage During Charging (16 V)					
22	5/2/5	6/16/3.2	109	0.546	45.4
23	5/2/5	3/16.5/.5	93.45	0.472	38.92
24	5/25	5/16/0.5	89.25	0.453	37.19
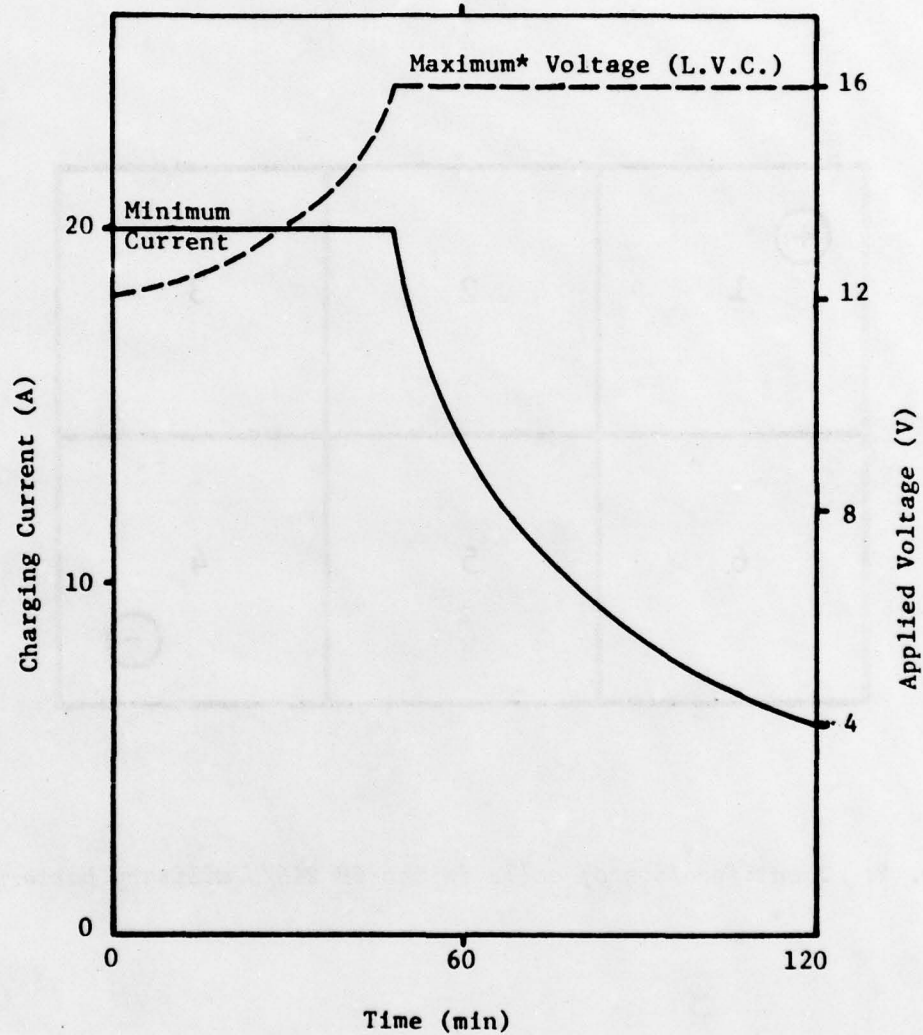
Fig. 1: *Typical variation of current and applied voltage versus time during a charge at low temperature. (* 14.25 or 16 V).*
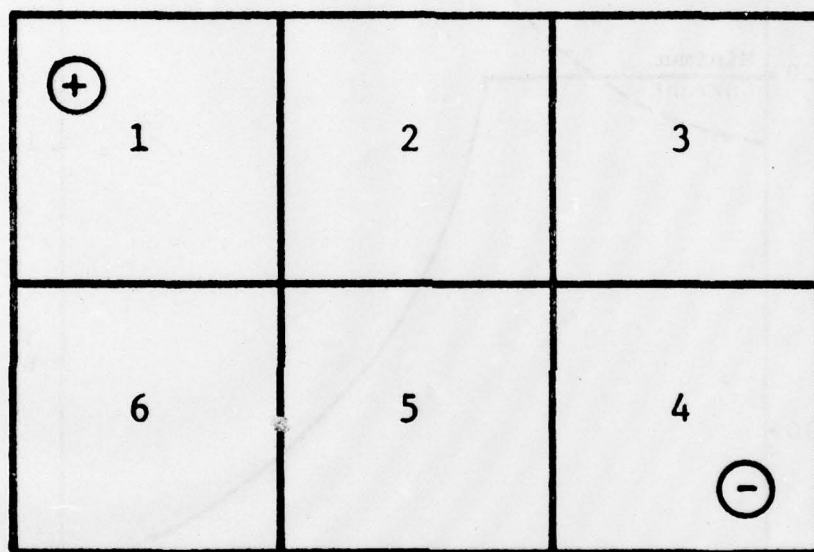
Fig. 2: *Identification of cells in the BB 248/U military battery.*

Fig. 5: Initial battery temperature and maximum current corresponding to each cycle (from values of Table II) (LVC of 14.25 V).

A: 25 A
B: 300 A
C: 285 A

● Discharge
+ Charge

Number of Cycles
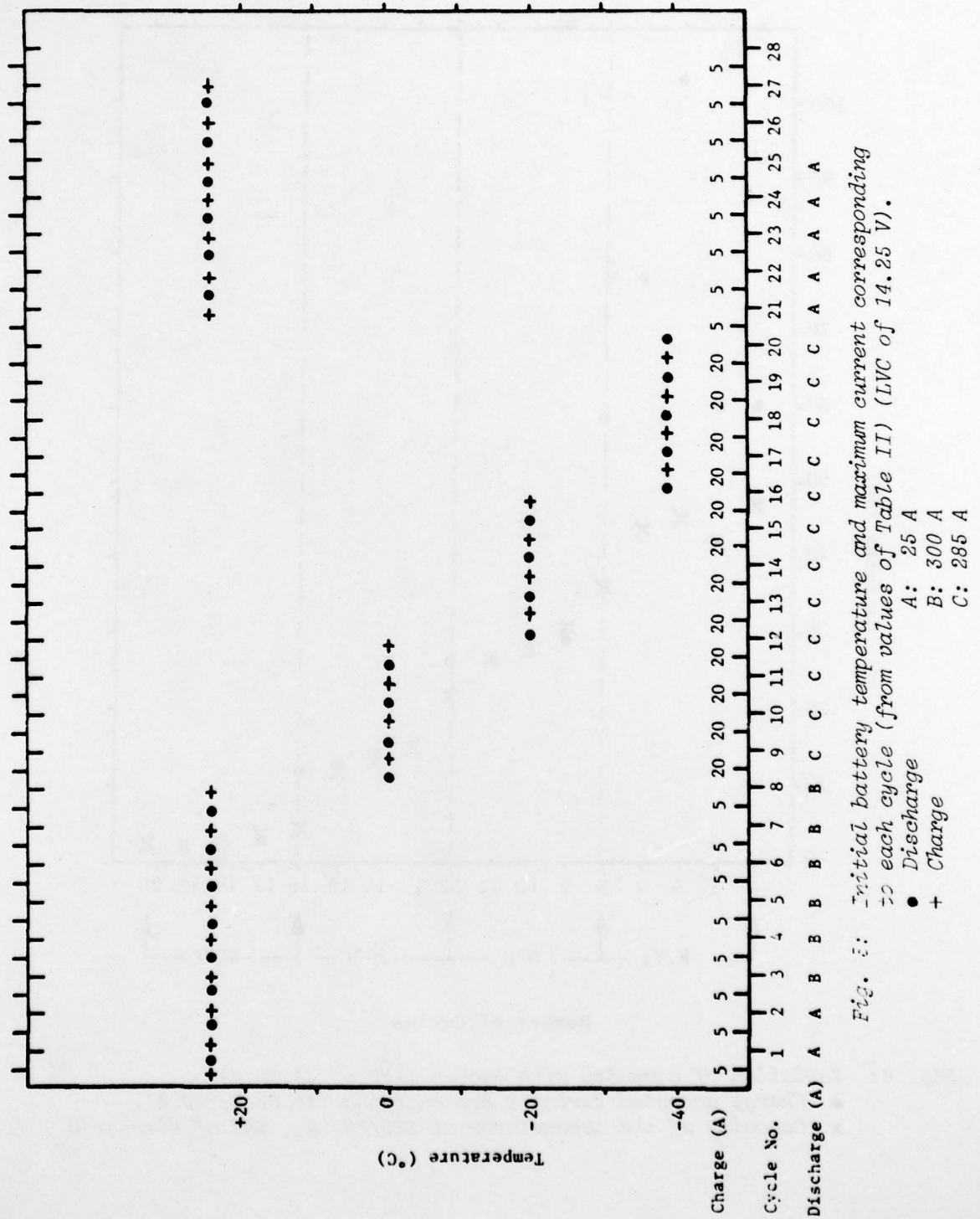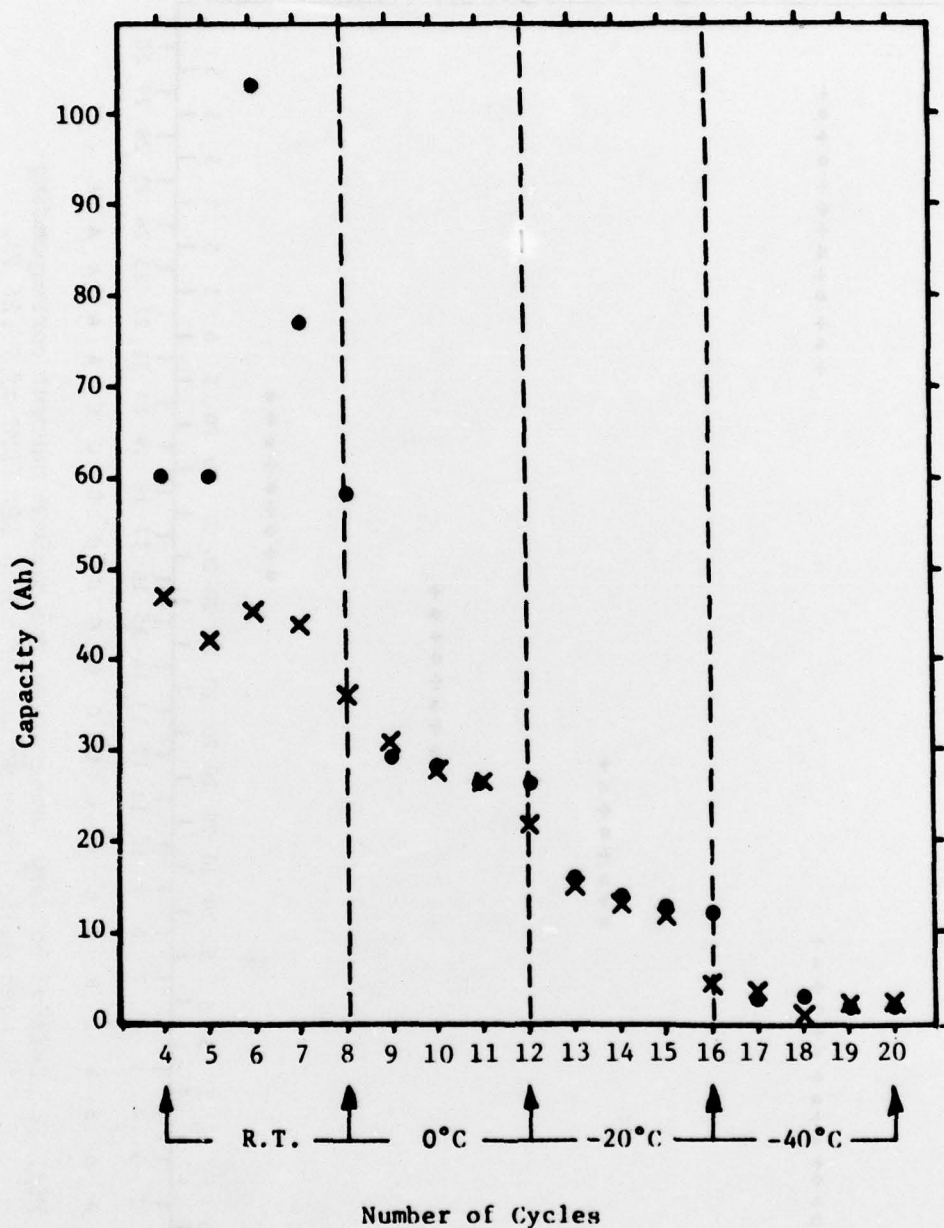
Fig. 4: *Variation of capacity with cycles (LVC of 14.25 V).*
* *Charge accepted during 2 hrs charging (14.25 V, 20 A).*
x *Capacity of the accumulator at 285/300 A. End of discharge 6 V.*
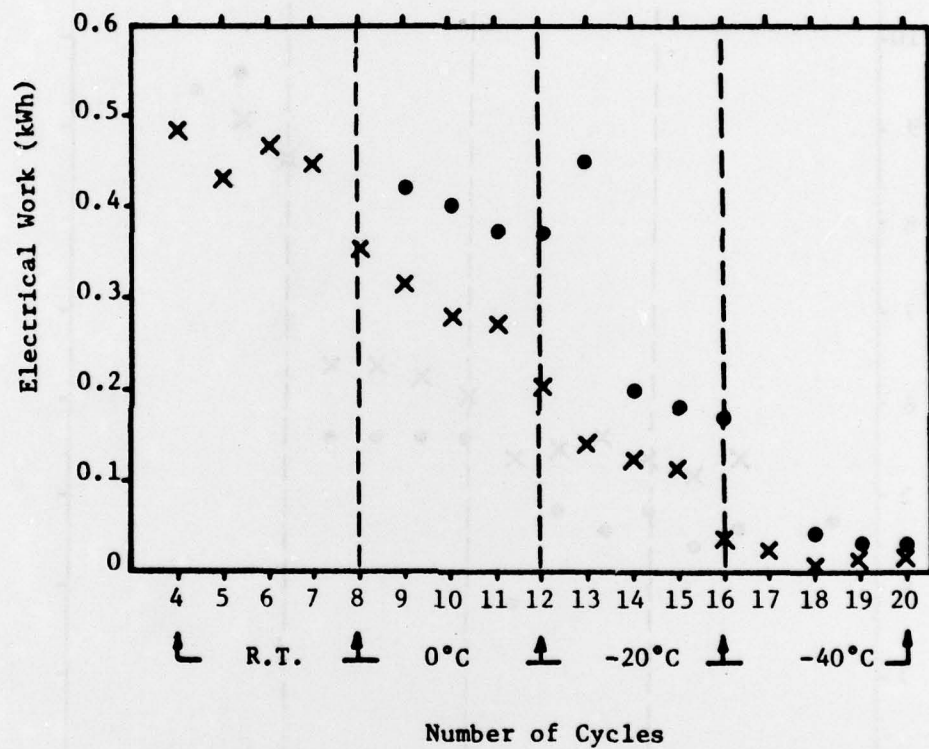
Fig. 5: *Variation of electrical work with cycles (LVC of 14.25 V).*
    ● *Electrical work accepted during 2 hrs charging (14.25 V, 20 A).*
    x *Electrical work done by the system. End of discharge 6 V.*
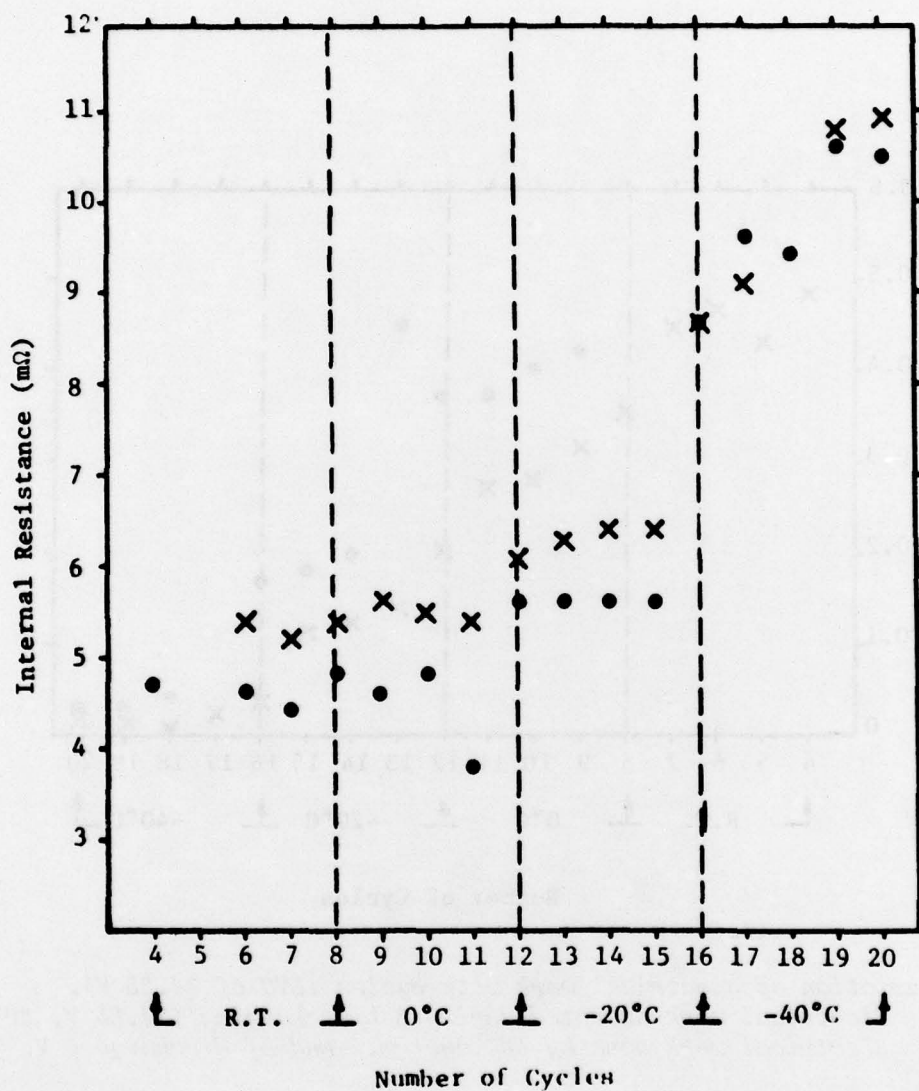
Fig. 6: *Internal battery resistance versus charge-discharge cycles*
(LVC of 14.25 V).
● Before a discharge.
x After a discharge.
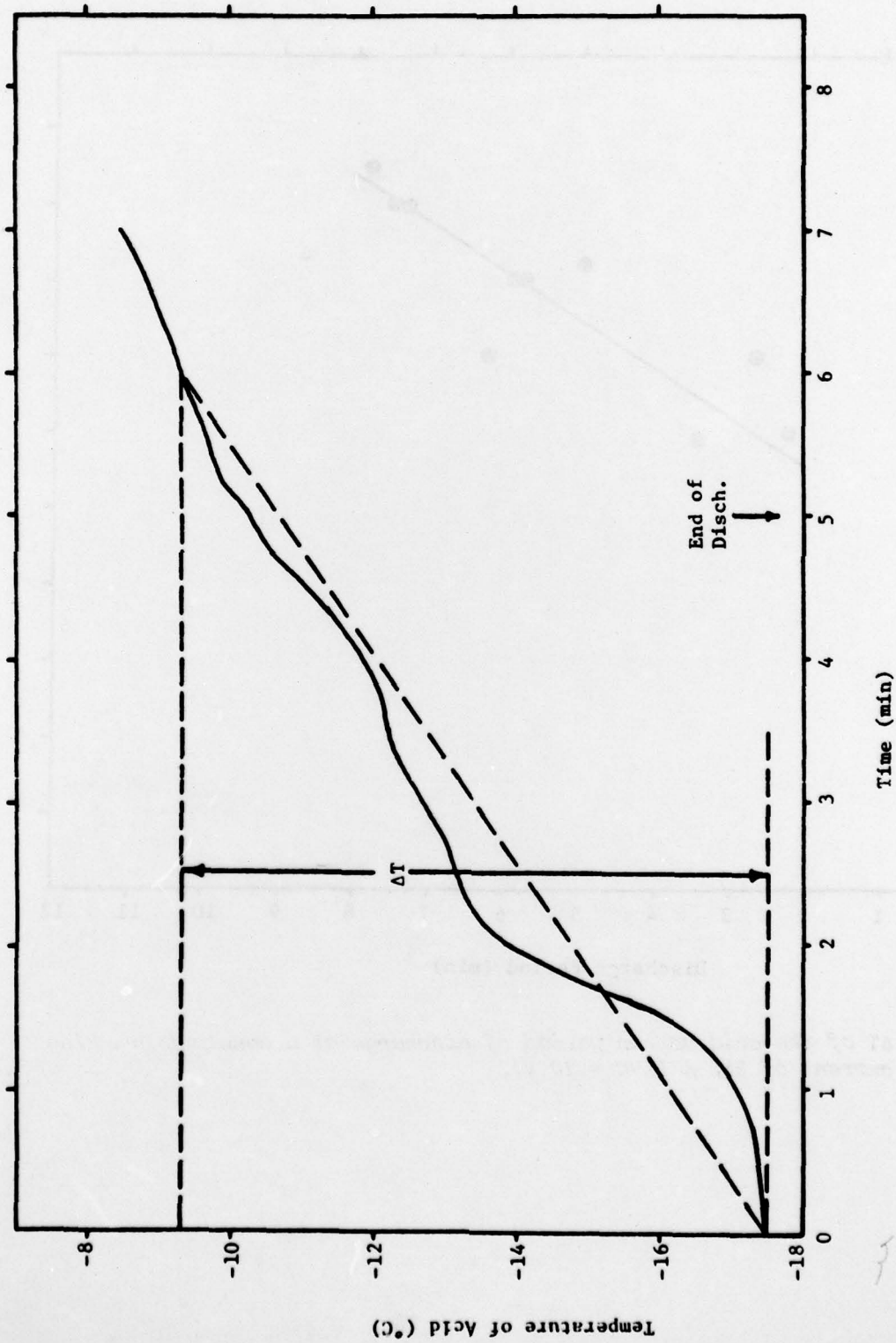
Fig. 7: Change in acid temperature during a discharge at 285 A. The cold soak temperature was -20°C and LVC was 16 V.
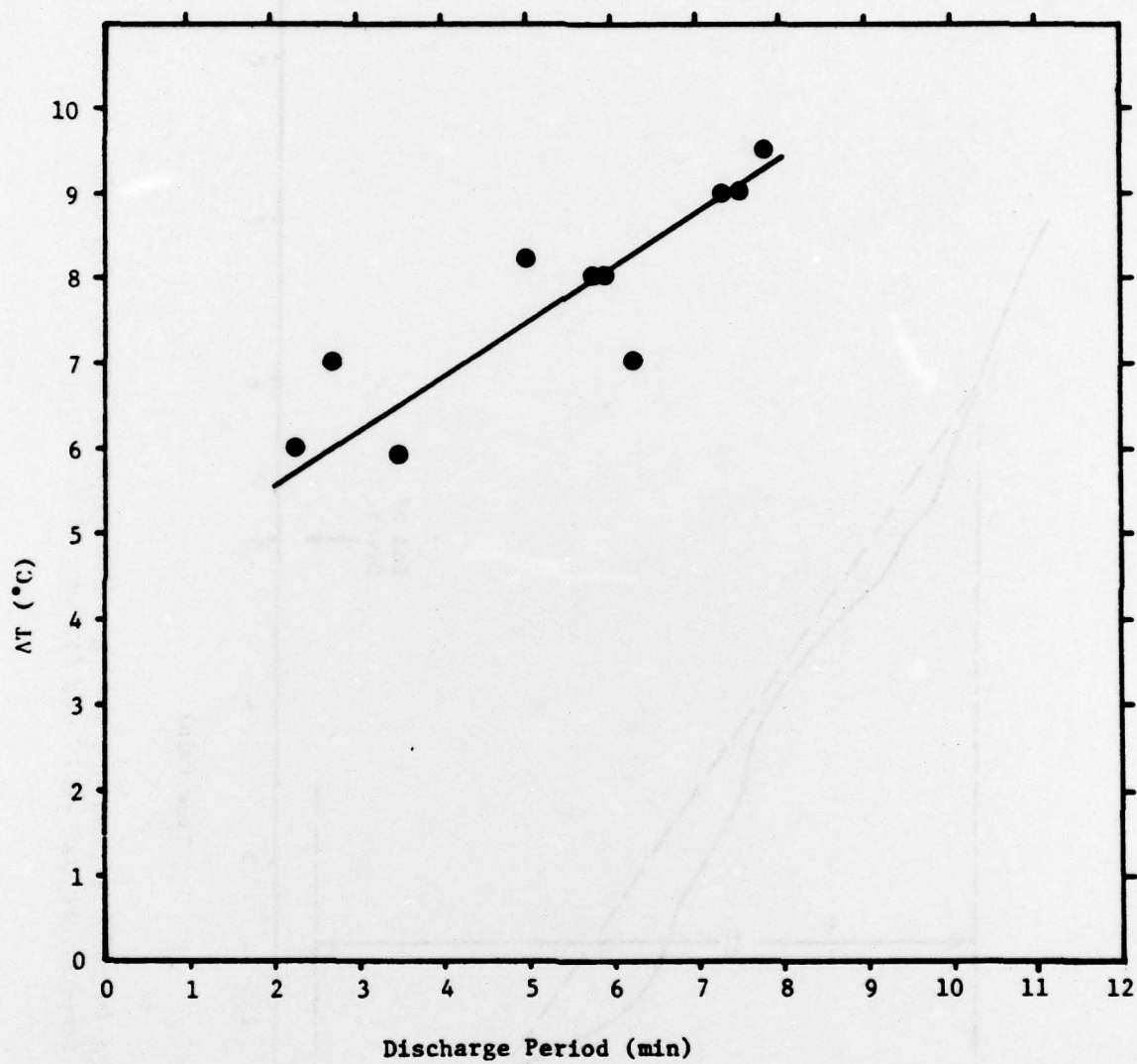
Fig. 8: ΔT of the acid versus period of discharge at a constant cranking current of 285 A (LVC = 16 V).

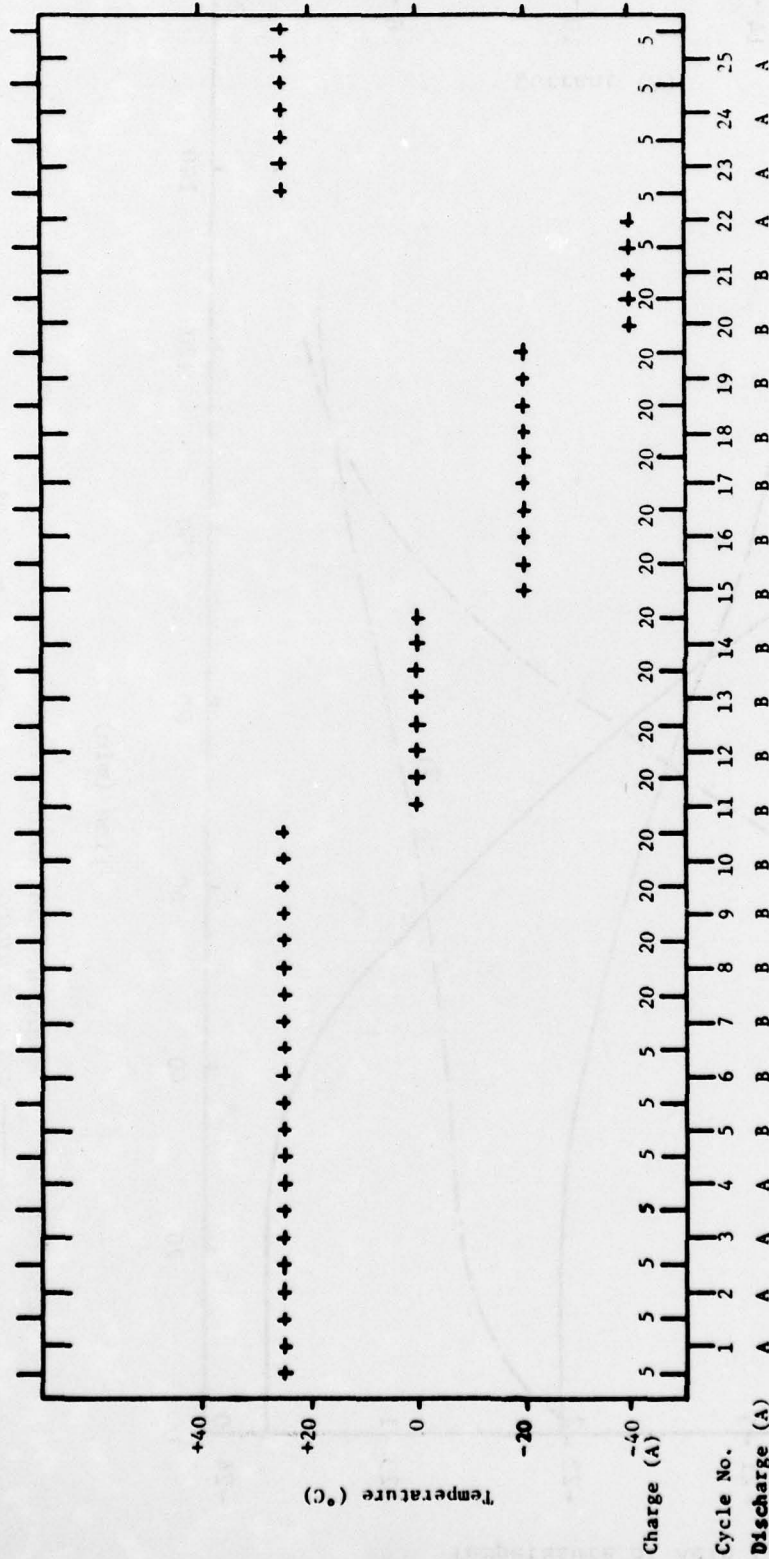Fig. 9: *Initial battery temperature and currents corresponding to each cycle (LVC of 14.25 V).*
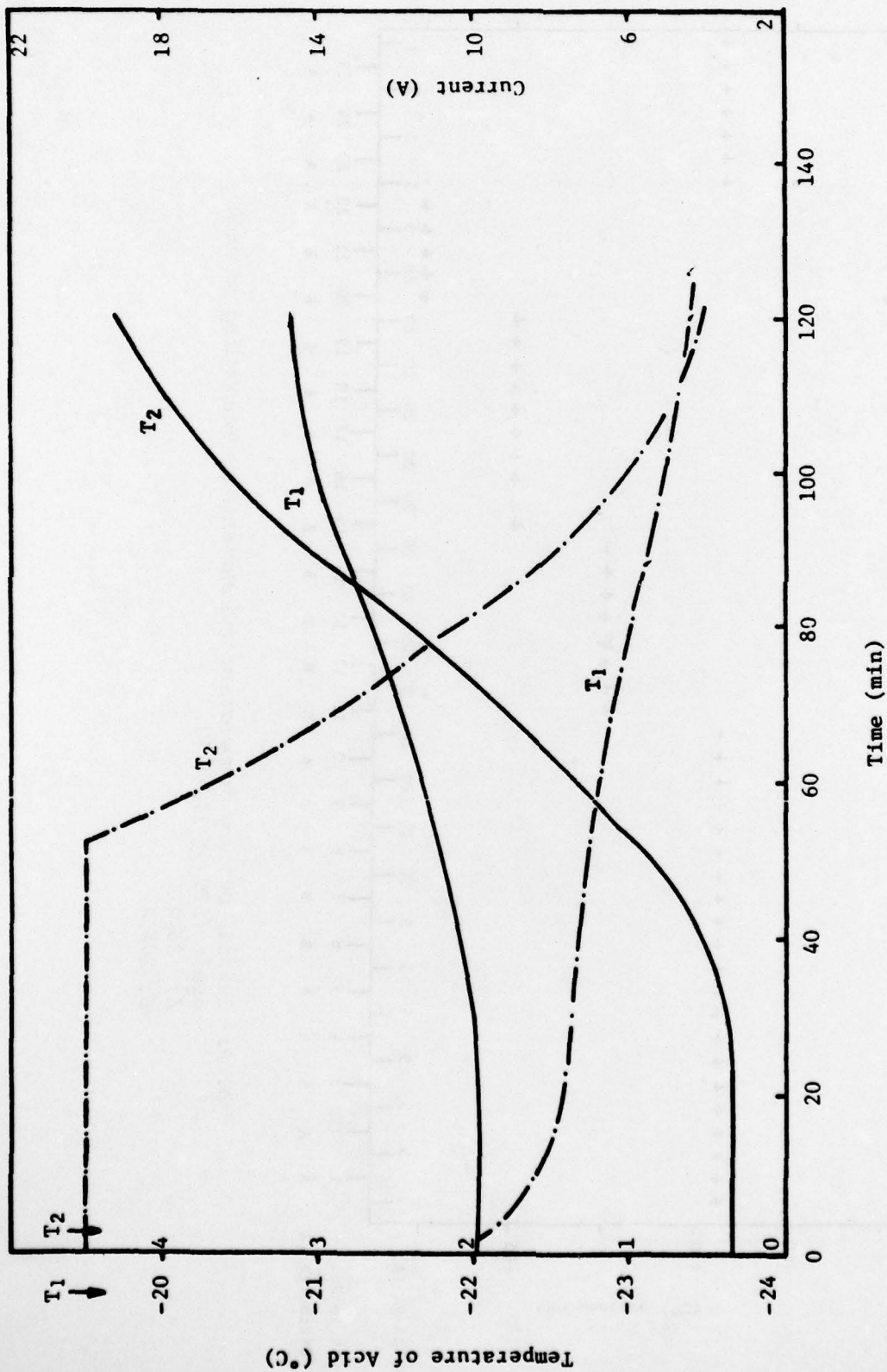*A: 25 A*
B: 285 A

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Fig. 10: ..... temperature and charge current versus time at 0° and -22°C.
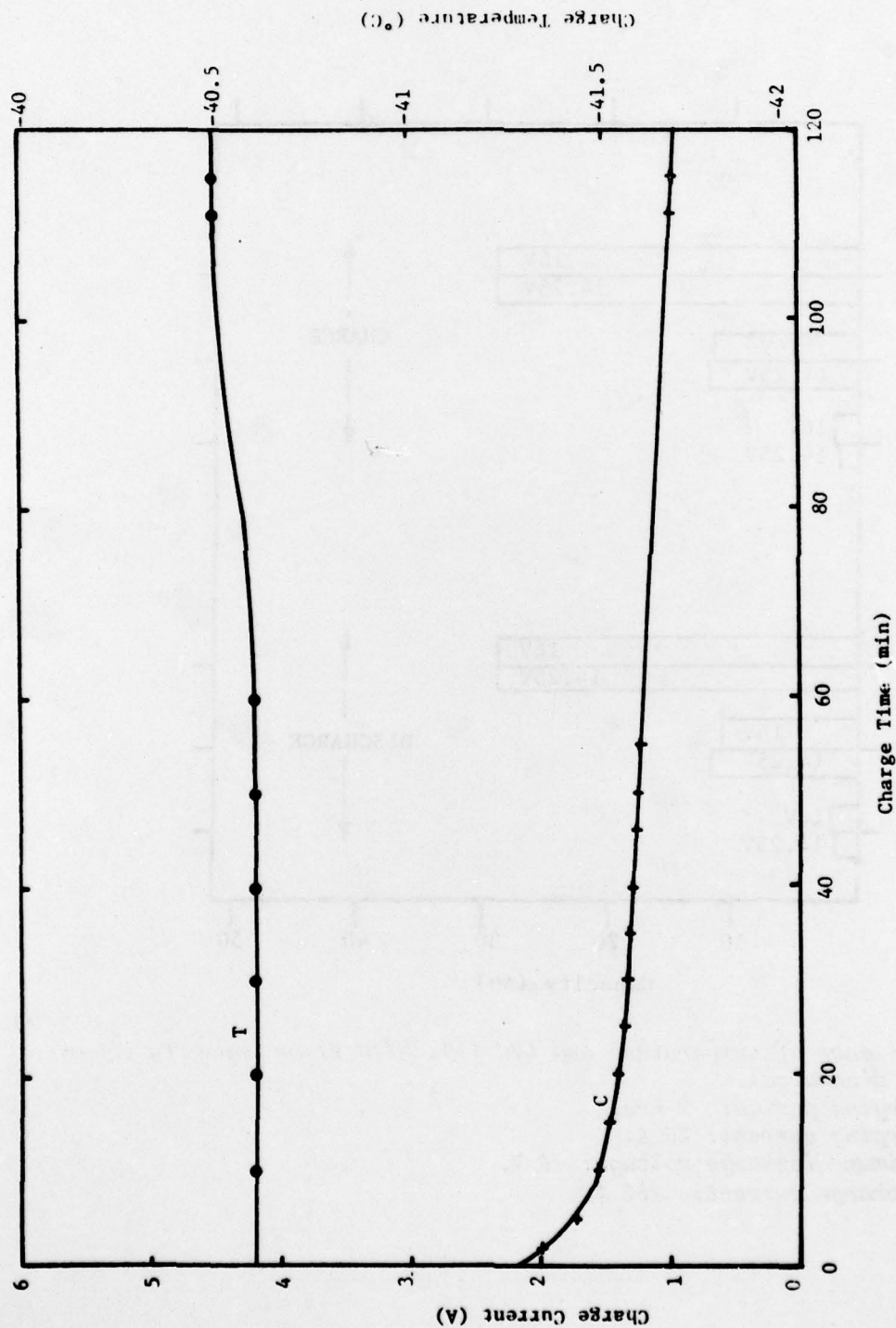— : Temperature   T₁ = -22°C   T₂ = 0°C
—·— : Current

Fig. 11: Change in acid temperature and current during a charge with an ambient temperature of -40°C (LVC of 16 V).
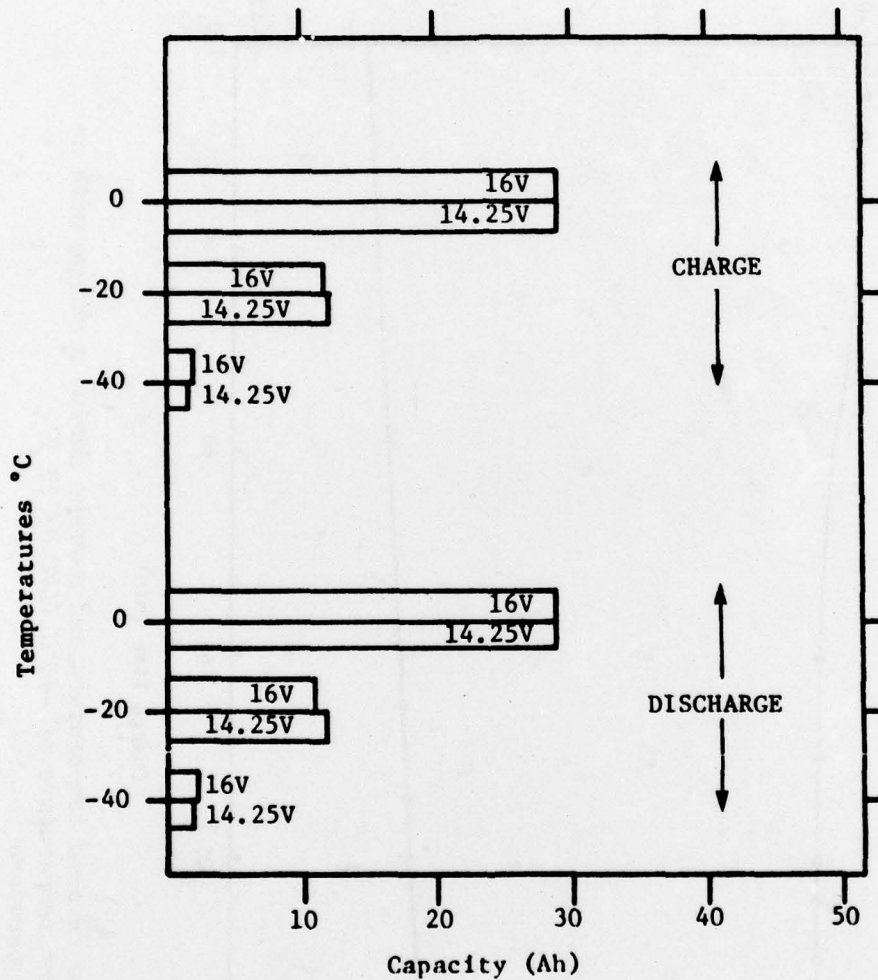
• Temperature
+ Current

Fig. 12: *Influence of temperature and LVC (14.25/16 V) on capacity (charge and discharge).*
Charging period: 2 hrs.
Charging current: 20 A.
Minimum discharge voltage: 6 V.
Discharge current: 285 A.

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13. ABSTRACT

The behaviour of the lead-acid battery type BB-248/U has been studied during many consecutive charge-discharge cycles. The cranking current and the minimum terminal voltage were 285 A (or 300 A) and 6 V, respectively. The working temperature was successively room temperature, 0°C, -20°C and -40°C while the rechargeability period was only 2 hours.

This work shows that such a rechargeability period - with a maximum charge current and an applied terminal voltage of 20 A and 14.25 V (or 16 V), respectively - is far too short to completely recharge the battery. Moreover, the rechargeability rate is only very slightly affected by the value of the maximum applied terminal voltage in the range of 14.25 V to 16 V. Finally, a significant decrease of reserve capacity measured at room temperature has been observed after many charge-discharge cycles at low temperatures.

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CHARGING VOLTAGE

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